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The Effect of Mean Stress on Corrosion Fatigue Life

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Abstract

An experimental investigation of the effect of mean stress on the fatigue life and corrosion fatigue life of cylindrical specimens is presented. Force controlled constant amplitude axial fatigue tests in the regime of 10^5 to 10^7 cycles were conducted for two different environments: in air (without corrosion) and in-situ in a corrosive environment, 0.824% $NaCl$ aqueous solution flow. The test results are assessed with respect to various standard models of mean stress influence on fatigue. The reduction in material fatigue strength due to the corrosion environment is evaluated and the results obtained show that in a low salinity aqueous corrosive solution, the fatigue strength at $4x10^6$ is reduced of a factor of 2 compared to no corrosion tests.

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Keywords: Corrosion fatigue; mean stress; fatigue strenght; high cycles fatigue.

1. Introduction

Corrosion fatigue failure is relevant many industrial fields, including the mining industry, where pump components are design to operate under cyclic loading in corrosive environments. The effect of mean stress in such components is of high importance in the design process, as it can significantly influence fatigue strength. Low carbon steel is widely used in the mining industry because its cost and mechanical properties. The main problem with this material is that is affected by environmental conditions and is susceptible to corrosion.

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Many studies have been conducted to understand how corrosive environments affect fatigue life of steel [1] and how the corrosion fatigue strength of the material decreases. Usually, sea water conditions are tested and many data are available in literature relevant to this condition. However, other corrosive environments have received less attention in research and, consequently, less data are available. This study considers corrosion fatigue behavior in a fresh water environment.

The effect of mean stress on fatigue life is a long established research topic. Several models have been proposed to describe its effects of the on the fatigue limit and more generally on material fatigue strength [2-6]. Several comparison of these different methods have been done to understand which of them better predicted the material behavior and many materials, including low alloy steel, have been compared [7,8]. However, the effect of corrosion has not been taken in account in these models. Recently some workers have studied the effect of mean stress on crack propagation in corrosive environment but in these investigations the stress-life approach is not considered. This study aims to understand if mean stress models developed and validated from data for a non-corrosive environment, can fit with low carbon steel experimental data obtained in a fresh water corrosive environment.

2. Material and testing condition

2.1. Material description

The material investigated is a low carbon forged steel (S355J2G3+N). It is a popular type of structural steel, used in a variety of industrial application where both static loading conditions and dynamic loading conditions occur. Its chemical composition and mechanical properties under quasi-static monotonic tension are shown in Table 1 and Table 2.

Table 1.
Chemical composition of S355 (%)

C	Mn	Si	P	S	Cr	Ni	Mo	Al
0.2	1.32	0.34	0.009	0.002	0.01	0.03	0.01	0.042

Table 2.
Mechanical Properties

Young's Module [MPa]	Yield Stress [MPa]	Ultimate Stress [MPa]	Elongation [%]
172	258	500	35.6

2.2. Specimens and testing condition

Fatigue test were carried out in air at room temperature and in $0.842\%\ NaCl$ corrosive aqueous solution. Both fatigue test in air and in corrosive solution were performed using 6 mm diameter cylindrical specimens, as shown in Figure 1. The specimen geometry was designed according to ASTM E466-07 [9]. The roughness of the gauge length surface was evaluated for each specimen through the arithmetic mean of four different measurements. Values were between Ra=0.095 micron and Ra=0.130 micron.

An environment chamber for corrosion fatigue tests compatible with a servo-hydraulic testing machine was designed and manufactured. The chamber allows a continuous flow of aqueous corrosive environment during the application of dynamic loads. The chamber encases the test specimen so as to allow the corrosion of its central part during the fatigue test, as shown in Figure 2.

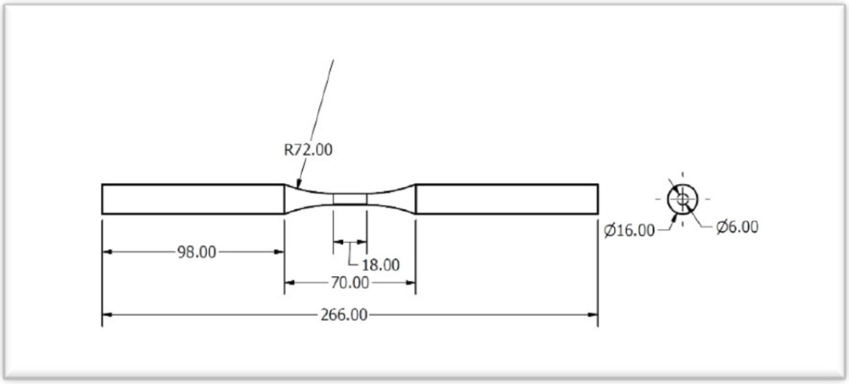

Fig. 1. Specimen geometry for fatigue test in air and corrosive environment

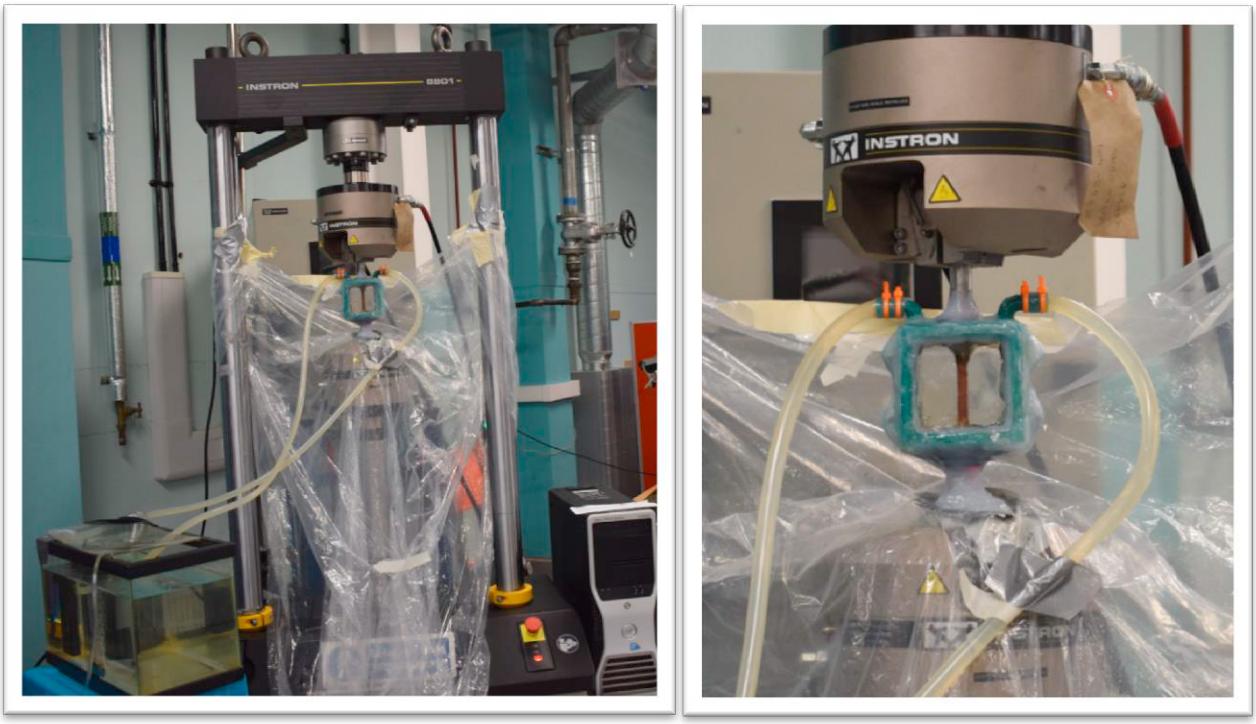

Fig.2 Corrosion system and detail of the chamber

The test chamber inlet and outlet diameter are 9 mm. To create the circulation of solution during the test, the inlet of the chamber was linked through a plastic pipe to a water pump with nominal flow of 600l/h placed in a tank. From the outlet the aqueous solution was returned to the tank through the same dimension plastic pipe. An air pump of nominal capability of 100 l/h was located in the tank to oxygenate the water during the test. Characteristics of the aqueous corrosive solution are given in Table 3.

Table 3.
Characteristics of aqueous solution environment

Temperature	Salinity	Conductivity	pH	Flow
25 ± 1°C;	0.84% $NaCl$	$2.0 \pm 0.2\ mS$	6.9 ± 0.1	130 l/h

Fatigue tests in air were carried out under axial loading and load control on a servo-hydraulic Instron $250\ kN$ machine. The frequency of all tests in air was fixed at 15 Hz. Fatigue tests in aqueous solution were carried out under axial loading and load control on a servo-hydraulic Instron $100\ kN$ machine. All the corrosion fatigue tests were performed at 10 Hz.

3. Experimental results and discussion

3.1. Fatigue in air and corrosion fatigue results

Fig. 3 shows S-N curves for the low alloy steel the following conditions:

- Fully reversed fatigue loading ,stress ratio $R = -1$, in air at room temperature;
- Positive mean stress, stress ratio $R = 0$, in air at room temperature;
- Fully reversed fatigue loading ,stress ratio $R = -1$, in 0.824% $NaCl$ aqueous solution;
- Positive mean stress, stress ratio $R = 0$, in 0.824% $NaCl$ aqueous solution

The results are plotted in semi-Log scale. Fig. 3 shows the effect of positive mean stress both in air and in corrosion environment. The trend shown in air is the typical behavior of steel under positive mean stress loading condition. Under positive mean stress the fatigue strength decreases and the fatigue limit appears at lower number of cycles.

A similar trend is observed for the corrosive environment: positive mean stress negatively affects the fatigue life and fatigue strength decreases compared to that obtained in a fully reversed load condition.

Fig. 3 show a decrease in the fatigue strength for specimens tested in the corrosive environment compared with specimens without corrosion. At 4×10^6cycles, the fatigue strength of a specimen cycled under fully reversed load in corrosion is$115\ MPa$. That is a decrease of 47% compared to the non-corroded specimen ($214\ MPa$). At the same number of cycles, the fatigue strength of a specimen under positive mean stress tested in a continuous corrosive flow is 88 MPa, a decrease of 51% compared to the non-corroded specimen under the same mean stress ratio (180 MPa) and a decrease of 59% compared to the non-corroded specimen under fully reversed load.

Similar trends have already been found by Pérez-More et al. [11] for a martensitic-bainitic hot rolled steel in a saline corrosive environment. The results presented in [11] were for an artificial sea-water environment that represents higher salinity than the fresh-water environment considered here ($0.824\%\ NaCl$).

Each S-N curve from Fig. 3 can be expressed using Basquin's equation:

$$\sigma_A = a \times N^{-b} \tag{1}$$

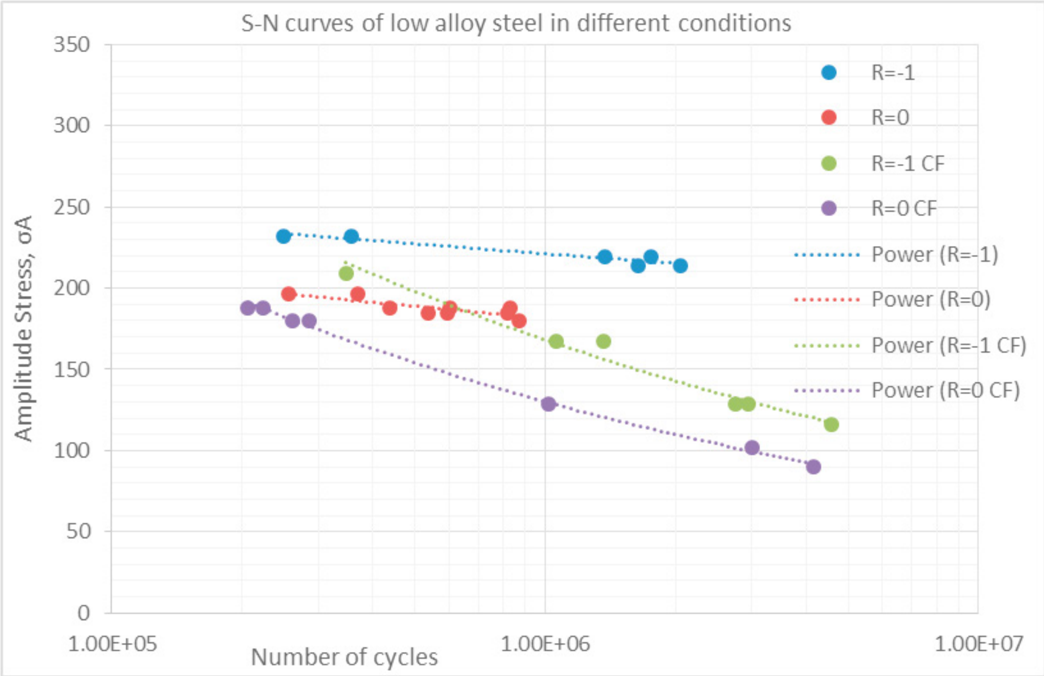

Figure 3: S-N curves of low alloy steel in different conditions

3.2. Mean stress analysis

In order to analyze the effect of mean stress in the corrosive environment, different relations have been considered to understand how they correspond with the experimental data. As the tests were carried out in load controlled condition, the main relations used in this analysis are based on the stress-life approach. A similar approach was used by Dowling [7] for several steel and non-ferrous metal to understand which model best represented experimental data. Here only one material is considered but for both in air and corrosive environments. The four mean stress models considered are:

- Modified Goodman relation:

$$\frac{\sigma_A}{\sigma_{eq}} + \frac{\sigma_m}{\sigma_u} = 1 \tag{2}$$

- Geber parabola relation:

$$\frac{\sigma_A}{\sigma_{eq}} + \left(\frac{\sigma_m}{\sigma_u}\right)^2 = 1 \tag{3}$$

- Smith-Watson-Topper Approach, (SWT):

$$\sigma_{eq} = \sigma_A \sqrt{\frac{2}{1-R}} \tag{4}$$

- Walker relation:

$$\sigma_{eq} = \sigma_A \left(\frac{2}{1-R} \right)^{\gamma} \tag{5}$$

where: σ_A is the stress amplitude, σ_m is the mean stress, R is the stress ratio, σ_{eq} is the completely reversed stress expected to cause the same life as the actual combination of amplitude and mean, (σ_A, σ_m) , σ_u is the ultimate strength and γ is a mathematical parameter that may be changed to better fit the equation to experimental data.

Each method has been used to calculate the combination of mean stress and alternating stress (σ_m, σ_A) that causes material failure at certain number of cycles. To calculate corresponding pairs of stresses, the value of number of cycles, N_i, is fixed between 10^5 and 10^7. In the S-N curve for fully reversed loading condition (R=-1), for each fixed value of N_i the corresponding value of sigma alternating, $\sigma_{A(R=-1)}$, is used to calculated stresses (σ_m, σ_A) required to cause the fracture at the same number of cycles. This value of sigma alternating is the equivalent alternating stress, σ_{eq}, defined above and required in all of the considered methods to evaluate the effect of mean stress. This calculation has been done using both fully reversed alternating stress for S-N curve in air (without corrosion) and in corrosive environment.

From each pair of mean and alternating stress calculated with the five different approaches, Equation 1 has been used to evaluate the experimental number of cycles at which samples have been broken. The predicted number of cycles, for each method, has been plotted in a logarithmic scale against the observed data. Figure 4 to 7 show the results.

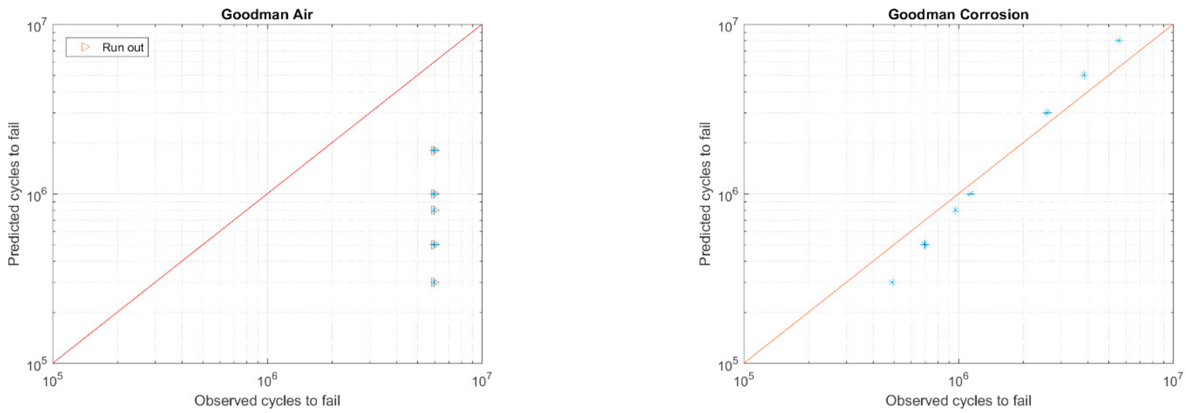

Figure 4: Predicted against observed fatigue life using Goodman criterion a) in air, b) in corrosion

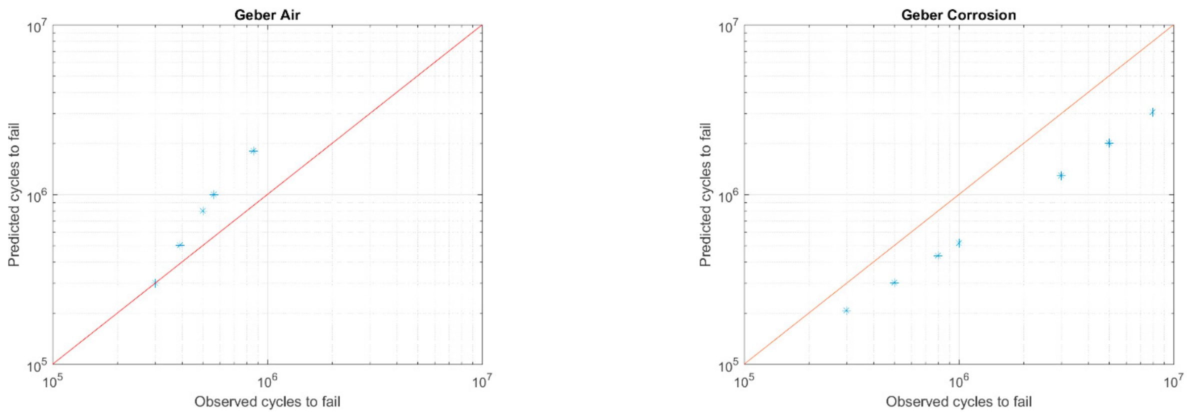

Figure 5: Predicted against observed fatigue life using Geber criterion a) in air, b)in corrosion

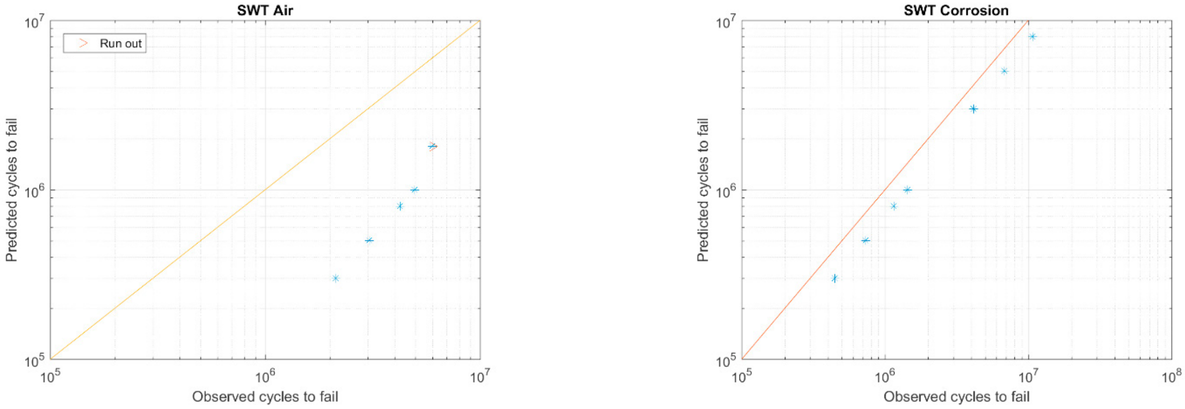

Figure 6: Predicted against observed fatigue life using SWT criterion a) in air, b) in corrosion

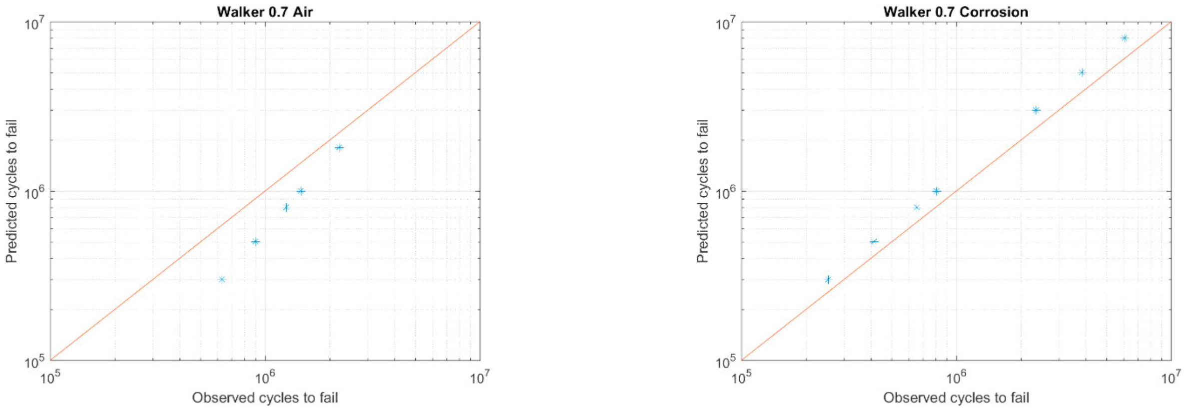

Figure 7: Predicted against observed fatigue life using Walker criterion a) in air, b) in corrosion

Goodman and SWT criterions result too conservative when applied with data obtained in air, as showed in Figure 4a and 6a. However predicted number of cycles with both models give a better fit in corrosion environment, even if Goodman criterion in high number of cycles gets non-conservative. Geber prediction has an opposite trend in air and in corrosion: indeed, predicted fatigue life in air is non-conservative but it is fixing better in corrosion with a conservative prediction.

Walker criterion has the advantage of fit data using the γ parameter that is actually calculated in order to give the best fit with data. Using a value of γ=0.7, therefore, it appears the best fit for data presented in this paper.

4. Conclusion

This study presents the experimental results of the effect of fresh water environment on fatigue strength and the effect of mean stress on corrosion fatigue life for a low carbon steel.

Experimental results show that the effect of the fresh water environment is to reduce the fatigue strength of the material: the degradation is higher at lower level of stress but occurs even at lower number of cycles. At 4×10^6 cycles the fatigue strength for specimens under fully reversed cycles is decreased by 47% compared with non-corroded sample. At the same number of cycles, the specimens tested with a stress ratio R=0 present a reduction in the fatigue strength of 51% compared to the fatigue strength of non-corroded specimens. A fatigue limit is not observed for either stress ratio considered. Further investigation, with test in lower level of stress, is required to better understand if a fatigue limit could occur in a non-aggressive corrosion environment.

The effect of mean stress has been presented using different predictive models widely known in literature. Models have been applied to experimental data both from fatigue in air and corrosion fatigue. These predictive models are common in the study of mean stress and in the prediction of fatigue life in a non-corrosive environment. But it is not proven that they take into account the corrosion effect. It was found that the Walker equation fits both sets of data. In particular, when the material parameter γ has the value 0.7, the equation results the best fit for experimental result obtained in air and in corrosion.

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